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Steam-Curing and Steam Hardening of Concrete Building Tile

Architectural Engineering

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STEAM-CURING AND STEAM HARDENING OF CONCRETE BUILDING TILE

BY

JAMES RALPH MONTIGEL
AND
LAWRENCE ORVILLE STOCKER

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ARCHITECTURAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

1912

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UNIVERSITY OF ILLINOIS

June 1, 1912

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

JAMES RALPH MONTIGEL and LAWRENCE ORVILLE STOCKER

ENTITLED STEAM-CURING AND STEAM-HARDENING

OF CONCRETE BUILDING TILE

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Architectural Engineering

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226374

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THE STEAM-HARDENING AND STEAM-CURING OF CONCRETE BUILDING TILE.

Introduction.

The rapid advancement in the uses of concrete building blocks in the past few years, has lead to a thorough investigation of the making, and curing of concrete products. A few experiments have been made to determine the strength of concrete blocks cured in steam, although little has been done to investigate the effect of steam-hardening, and steam-curing of concrete. The term steam-hardening is used to designate the process of giving the concrete an initial set in steam, and steam-curing the process of curing after it has had an initial set.

That the hardening of portland cement is accelerated when subjected to heat after hydration is a well known fact, yet little data are available to show to what degree this may prove of value commercially. Without attempting to investigate the economical phase of the problem it has been the prime object of this series of tests to determine the effect on the strength of building tile resulting from steam-curing.

It has been generally considered that a wet mixture produces the best grade of concrete, but by the use of a wet mixture the block manufacturer is required to have a large supply of molds, which has proved to be not only expensive, but impracticable, except in the larger plants. With this fact in mind, it was the secondary object to determine the

practicability of steam-hardening together with steam-curing of concrete building tile, whereby a wet mixture may be employed, giving it an initial set in steam, and removing the mold immediately, before placing in the steam-curing room. By this method the manufacturer could obtain a product of maximum density with the use of only a few molds, and procure the same results as by using many molds, and allowing the concrete to receive its initial set in the open air, providing the concrete is found to attain the requisite strength.

Information concerning the processes employed in steam-curing of concrete products was received from various sources among which were : Mr. C.J.Davis, Timewell, Illinois; Ewing Contracting Co, Bloomington, Illinois: Helm Pressed Brick Co, Traverse City, Michigan, and The Waterloo Concrete Machinery Co, Waterloo, Iowa. They unanimously claim that steam-curing gives far better results than can be obtained by curing in the open air, and that the product is not only more uniform in color, but also more uniform in quality. The steam-curing process was found to be more economical than curing in air.

A series of tests by Robert F. Havlik, and Rudolph J. Wig were made at the Structual Materials Testing Laboratories at St. Louis and published in Technologic Papers of the Bureau of Standards, No. 5, 1912. A few of the results of these tests are given in Tables 1 and 2. The test pieces used in these experiments were cylinders and they withstood a high compressive strength.

The process of steam-hardening has received less

attention than steam-curing, but in this like the many other undeveloped fields in concrete engineering there seems to be an excellent opportunity for investigation. The Concrete Steam and Sand Co. of Youngstown Ohio have had the best success with this process and the results of their tests show that steam-hardening should revolutionize the concrete building tile industry. The structual tile are molded in specially designed machines in steam heated molds; the excess water is driven off by the steam; the tile is mechanically ejected from the mold, and then treated by the steam-curing process. From tests made at The Pittsburg Testing Labatory on a specimen of 62 sq.in. sectional area an ultimate strength of 1,003 lb. per sq. in. was obtained.

Results of Steam-Curing Tests of Portland Cement Mortars.

(From Technologic Papers Bureau of Standards, No.5, 1913).

The test specimens consisted of 8 in. by 16 in. cylinders.

Table 1.

One part portland cement to four parts sand. Damp consistency (9 per-cent water). Tested when 2-days old.

Spec. No.	Cured in Steam, hours.	Temp. of Steam.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq.in.
1	---	---	33,880	670
2	---	---	29,810	590
3	---	---	28,710	567
4	48	212 F	62,380	1,241
5	48	212 F	68,570	1,364
6	48	212 F	60,050	1,195

Table 2.

One part portland cement to four parts sand. Damp consistency (9 per-cent water). Tested when 7-days old.

Spec. No.	Cured in Steam, hours.	Temp. of Steam.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq.in.
25	---	---	67,860	1,345
26	---	---	62,030	1,240
27	---	---	65,430	1,302
28	24	212 F	84,000	1,671
29	24	218 F	95,490	1,899
30	24	218 F	91,140	1,815

Outline of Tests.

There were four series of investigations:(1) To determine the effect on concrete when set in air, and cured in steam; (Tested at 7 and 28 days). (2) To determine the effect on concrete when given a partial initial set in steam, and cured in steam using a wet consistency of mortar;(Tested at 7 and 28 days). (3) To determine the effect on concrete when given a total initial set in steam using a sloppy consistency of mortar;(Tested at 7 and 28 days). (4) To determine the porosity of steam-cured and air-cured concrete building tile made from mortar of different consistencies.

Since it was desired that the results of these experiments should agree with such results as might be obtained in practice, the same mixture was used throughout, but with a variation in the percentage of water used in mixing. The same temperature of steam was maintained in the steam-curing charber during all the tests, the steam at atmospheric pressure (212°F), this being considered the temperature which could be most easily handled in practice.

The mortar consisted of one part Universal portland cement and four parts of bank sand from near the Wabash river at Attica Indiana. Briquette tests and other tests of this cement are given in Table A. The sand was well graded and had been screened through a 1/4-in. screen. Mechanical analysis of this sand are given in Table B. The cement and sand used were the same as that used for the other experiments conducted at the University of Illinois during the season 1911-12.

Different consistencies of mortar were used. They will be designated: Damp consistency, 9.7 per-cent water; Wet consistency, 13.5 per-cent water; Sloppy consistency, 18.5 per-cent water. Damp consistency contained an amount of water such that when a small quanity of the mortar was pressed and rolled lightly in the hand it would form a ball and showed no excess of moisture. Wet consistency contained enough water that when trowled lightly water was brought to the surface. Sloppy consistency contained enough water so that the mass could be poured from a bucket.

Table A.

BRIQUETTE TESTS OF UNIVERSAL PORTLAND CEMENT.

Each value is the average from five tests.
Loads are given in pounds per square inch.

Sample No.	Date	Neat Cement 7 Days	Neat Cement 28 Days	1-3 Mortar 7 Days	1-3 Mortar 28 Days
1	Oct. 25, 1911	585	685	239	315
2	Nov. 11, 1911	577	694	225	297
3	Dec. 7, 1911	691	715	242	306
4	Dec. 22, 1911	617	792	231	326
5	Jan. 10, 1912	588	672	246	333
6	Feb. 12, 1912	612	758	253	323
7	Feb. 28, 1912	698	884	287	372
Average		624	743	246	325

Additional tests on this cement showed the initial set to occur at 3 hours and 5 minutes and final set at 6 hours and 32 minutes after mixing. Sieve tests showed 97.2 per-cent passing a No. 100 sieve and 81.8 per-cent passing a No. 200 sieve.

The above tests were made according to the standard methods by Mr. B. L. Bowling at the Cement Testing Laboratory at the University of Illinois.

Table B.

MECHANICAL ANALYSIS OF SAND.

Each value is the average of five samples.

Sieve No.	Separation Size, inches.	Per-cent Passing.
3	0.23	100.0
5	.174	99.0
10	.091	54.3
12	.067	47.5
16	----	41.7
18	.043	36.0
30	.027	21.9
40	.019	13.7
50	.013	5.1
74	.009	2.7
150	----	1.0

Apparatus and Methods of Manufacture of Test Pieces.

A test piece 12 in. long, 6 in. wide, and 6 in. high with 1 in. walls and web, was selected, since it could be easily molded and the resulting values of compression tests would be similar to those of like specimens used in practice. The mold in which these test pieces were formed is shown in Fig. 1. It consists of the jacket and cores. The jacket is composed of two 6 in. channels 24 in. long placed back to back separated by end gates 12-1/4 in. apart. The iron hinges at the ends of the channels made it possible to close the form tight. The cores used in making all the test pieces, except the ones in which the sloppy consistency was used were as shown in Fig. 2. They were yellow pine blocks 4-1/2 in. by 4 in. and 8 in. high, fitted with a hook so that they could be pulled from the finished tile. Before using the cores they were thouroughly oiled.

All mixing of concrete was done by hand with shovels. The sand had remained in the air-curing room for over two weeks before using and was thoroughly dry. Four buckets of sand and one of cement constituted a batch, this being enough to make nine specimens. A large cast-iron mixing box was used. The sand and cement were mixed dry four times, then the water added and the mass turned three times. In every case enough concrete was mixed so that all the specimens for one experiment could be made from one batch.

Owing to the fact that there was no draft to the cores, it was necessary to construct an apparatus by means of which

the cores could be pulled vertically without injuring the specimen. This apparatus was constructed as shown in Fig. 3. A molding table fitted with wooden guides to receive the metal form made it possible to place the form in the same position each time, so that the apparatus could be placed and the cores lifted vertically with a minimium amount of friction.

The operation of making the test tile was as follows: The form was placed on the molding table and the cores placed. Sucessive layers of concrete about 1-1/2 in. thick were put in the form and thoroughly tamped with a 7/8 in. wooden tamp, care being taken that the cores were in the center and that the web and walls of the test piece had a uniform thickness of 1 in. When the form was filled, the template shown in Fig. 4 was placed over the form and the apparatus for drawing the cores put in place. The rods B-B were attached to the hooks in the top of the cores. A light pressure on the end of the lever was sufficient to draw the cores. After releasing the end hinges and removing the sides and end gates of the form, the tile was ready to be set away for curing.

The number per set for each experiment consisted of twelve specimens except in the cases where the capacity of the curing chamber limited it to a smaller number. Specimens were marked A,B,C,D,E, and F, according as they belonged to experiments 1,2,3,4,5, and 6. All test pieces were examined closely after making, for cracks or flaws which might have been caused by withdrawing cores or handling.

The molding apparatus for the steam-hardened tile was

the same as was used for those made from the damp and wet consistencies, except that metal cores made from No. 18 galvanized iron were used. In order to make it possible to remove these cores from the form it was necessary to use a split core as shown in Fig. 5. Wedges placed on the inside held the sides of the cores from springing during the molding process. The form was set as mentioned above and the concrete poured. The forms were then carried to the steam chamber and the steam turned on for two minutes. They were then taken to the molding table and the cores and jacket removed; the entire operation requiring an average of three minutes. All the specimens which had been hardened in steam were taken to the steam chamber for curing as soon as the cores and jacket were removed.

The steam-curing chamber is shown in Fig. 6. The chamber is 27 in. in diameter and 30 in. deep. It is made of No. 14 galvanized iron. The cover is made from 1-1/2 in. yellow pine boards, the underside being covered with No.22 galvanized iron and padded with rubber packing so as to make it fit tightly on the chamber. A 3/4-in. intake admits the steam from an overhead heating main. A small hole C was made to admit a thermometer.

The temperatures during hardening and curing were recorded as the experiments progressed. Four readings were taken each day during the process of steam-curing and the average recorded on the data sheet.

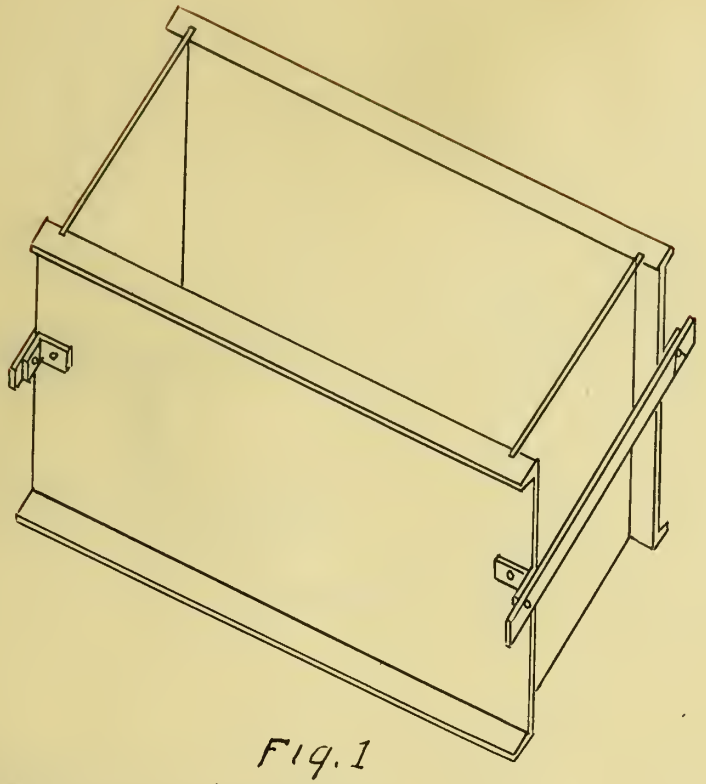

Fig. 1
Isometric View of Form

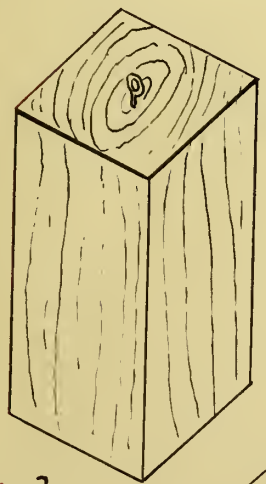

Fig 2

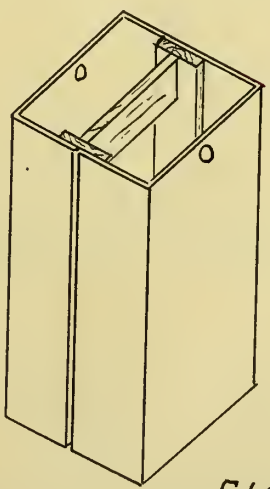

Fig. 5

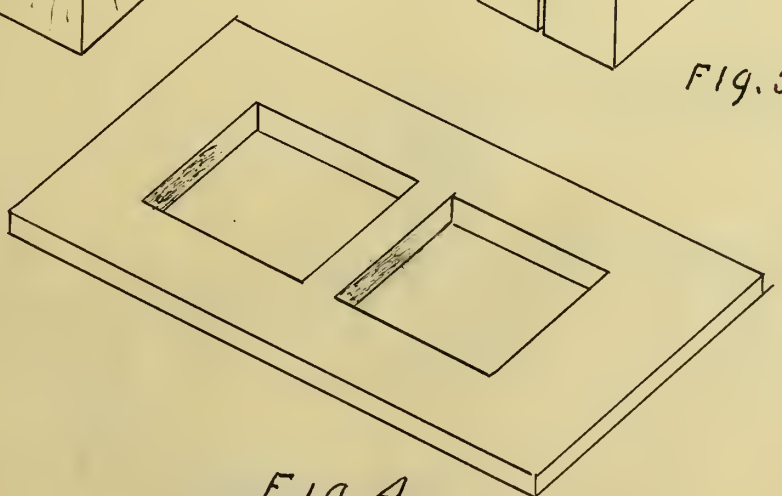

Fig. 4.

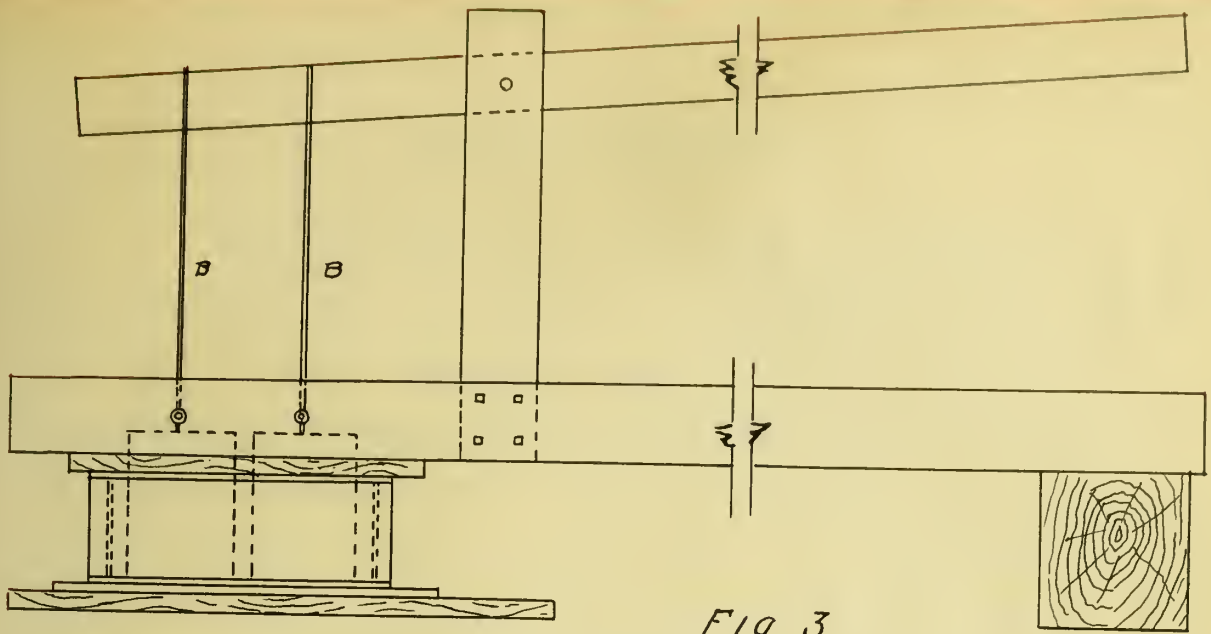

Fig. 3

Apparatus for Drawing Cores from Form.

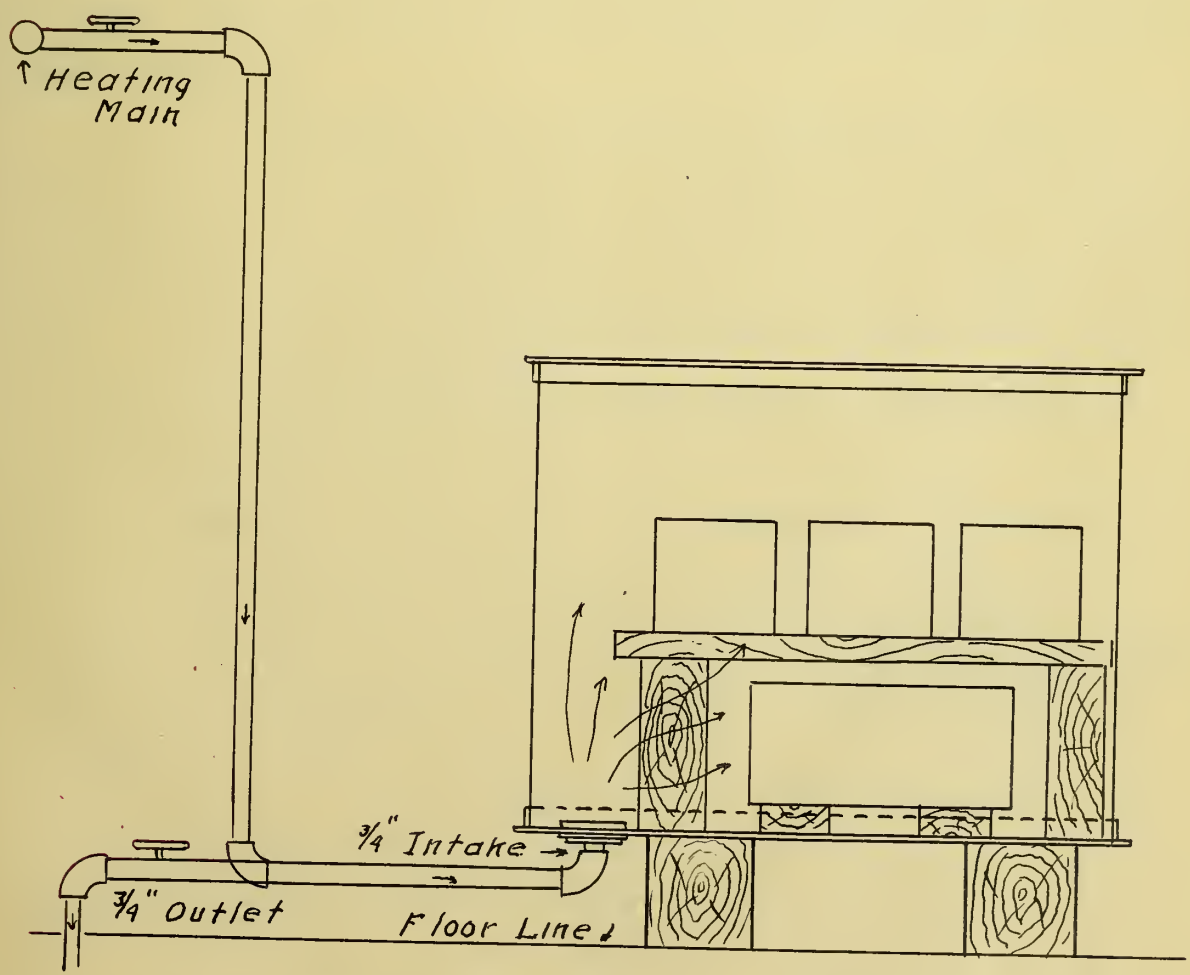

Fig. 6

Sectional View through Steam-Curing Chamber

Details of the Tests.

Before preparing the specimens for testing each one was weighed in order to compare the densities of the concrete. The top and bottom surfaces of each specimen were bedded in a thin layer of plaster of paris which was allowed to harden thoroughly before testing. The method of applying the plaster was as follows: A planed slate slab was leveled and thin paper laid on the slab to receive the plaster which was spread evenly about 1/4 in. thick. The tile was bedded in the plaster and kept as nearly vertical as possible. When the plaster had set the specimen was turned over and the other side bedded in the same manner.

The specimens were tested for compression only, with the applied force in the same direction as the line of tamping. A Riehle vertical testing machine of 100,000-lb. capacity was used. In placing the test piece in the machine, care was taken to have the specimen exactly in the center of the table. A spherical bearing block set on a 1-in. planed cast iron plate, made it possible to distribute the load evenly over the specimen. The load was applied at the rate of 1/10-in. per minute until failure occurred. The manner of failure of each specimen was noted, and the character of the concrete along the line of fracture.

EXPERIMENT 1.

TO DETERMINE THE RELATIVE COMPRESSIVE STRENGTH OF STEAM-CURED, AND AIR-CURED CONCRETE BUILDING TILE.

One part portland cement to four parts sand. Damp consistency 9.7 per-cent water. Tested when 7 days old.

Initial set in air 24 hours;
Average temperature of steam-curing chamber 210 F.
Average temperature of air-curing chamber 70 F.
Area of cross section 36 sq.in.
Volume of specimen 216 cu.in.

Spec. No.	Cured in Steam, hours.	Cured in Air, days.	Weight per cu. ft. when tested, pounds.	Load at Ultimate, pounds.	Ultimate strength pounds per sq.in.	Gain of steam-cured over air-cured specimens, per-cent.	Remarks.
A-1'	24	5	136	23,500	655		Crushed at bottom.
A-1"	24	5	134	24,400	680		Crushed at end.
Av.	24	5	135	23,950	668	14.0	
A-2	48	4	137	30,000	835		Sheared at end.
A-2'	48	4	135	35,800	995		Crushed at end.
A-2"	48	4	136	36,700	1,020		Crushed at end.
Av.	48	4	136	34,166	950	63.0	
A-3	72	3	135	33,800	940		Sheared at end.
A-3'*	72	3	137	29,800	830*		Sheared at end.
A-3"	72	3	137	35,400	980		Crushed at end and side
Av.	72	3	136	33,000	920	55.0	
A-4	--	6	134	23,400	650		Sheared at end.
A-4'	--	6	133	18,600	515		Crushed at end.
Av.	--	6	134	21,000	583	00.0	

* Crack in the specimen before testing.

EXPERIMENT 2.

TO DETERMINE THE RELATIVE COMPRESSIVE STRENGTH OF STEAM-CURED AND AIR-CURED CONCRETE BUILDING TILE.

One part portland cement to four parts sand. Damp consistency 9.7 per-cent water. Tested when 28 days old.

Initial set in air 24 hours.
Average temperature of steam-curing chamber 212 F.
Average temperature of air-curing chamber 76 F.
Area of cross section 36 square inches.
Volume of specimen 216 cubic inches.
Specimens were sprinkled for 7 days after removal from steam-curing chamber.

Spec. No.	Cured in Steam, hours.	Weight per cu. ft. when tested, pounds.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq. in.	Gain of steam-cured over air-cured specimens, per-cent.	Remarks.
B-1	24	136	42,000	1,165		Crushed at end.
B-1'	24	136	44,000	1,240		Crushed at end.
B-1"	24	136	40,000	1,110		Sheared at end.
Av.	24	136	43,300	1,172	14.7	
B-2*	48	137	28,700	800		Crushed at end.
B-2'	48	137	42,000	1,165		Crushed at end suddenly.
B-2"	48	137	42,000	1,168		Sheared at side.
Av.	48	137	42,000	1,165	14.0	
B-3	72	138	46,000	1,330		Crushed suddenly.
B-3'	72	138	54,500	1,515		Sheared at side, end.
B-3"**	72	139	32,000	890		Crushed suddenly.
Av.	72	138	51,250	1,423	39.3	
B-4	--	136	38,000	1,055		Cracked at side, end.
B-4'	--	134	34,300	955		Sheared at end.
B-4"	--	134	38,000	1,055		Sheared at side, end.
Av.	--	135	36,766	1,022	00.0	

* Unequal bearing in the machine.
** Crack in the specimen before testing.

Experiments 1 and 2.

Experiment 1 consisted of ten test pieces [illegible] as follows: series A-1, A-2, and A-3 were cured in steam 24,48, and 72 hours respectively and series A-4 cured in air only, all of which were tested when 7 days old. Experiment 2 consisted of twelve specimens, three in each series. They were cured in steam 24, 48, and 72 hours with the exception of the last series which was cured in air only. All the specimens were tested when 28 days old. Although the batches were mixed on different days, care was taken to get the same weight of concrete materials and water in each case. The concrete was placed in the form in layers so that it could be tamped well and evenly. When the test pieces were twelve hours old they were sprinkled, and when twenty-four hours old all were marked, and the ones to be treated in steam were placed in the steam-curing chamber, while the air-cured specimens remained in the air-curing room and were sprinkled three times per day for seven days.

The period of steam-curing was 24, 48, and 72 hours in both experimentsin order to determine the limit of the time required to produce the best results. After removing the test pieces from the steam-curing chamber, they were set aside until the time of testing; the 7-day specimens were sprinkled daily for two days and the 28-day specimens three times daily for seven days.

The results of the individual tests are recorded in the accompanying tables. These tests give the maximum compressive strength of 950 lb. per sq.in. for the 7 day specimens and

1,172 lb. per sq.in. for the 28 day specimens. The former were steam-cured 48 hours and the latter 24 hours. There is a more decided increase in the per-cent gain of the steam-cured test pieces over the untreated ones in Experiment 1, than in Experiment 2. This is probably due to the fact that the concrete cured in air only has a low compressive strength when 7 days old, but increases rapidly up to the time it is 28 days old. Examination of the average of the series A-4 and B-4 show an increase of 75 per-cent. However the steam-cured test pieces have a relatively high ultimate strength after a few hours steam curing and the increase after the steam treatment up to 28 days is less rapid. The ultimate compressive strength of the average of B-4 is 1,022 lb. per sq.in.while the average of A-2 is 950 lb.per sq.in, the latter was cured in steam 48 hours and tested when 7 days old, while the former was cured in air 7 days and tested when 28 days old. B-4 is 7.3 per-cent stronger than A-2. Allowing the test pieces the same treatment as before, but testing when 28 days old, the increase in the ultimate amounts to 14 per-cent as is seen by the average of B-2. In each case the increase in strength after removing from the steam-curing chamber is marked, as can be seen by reference to the accompanying tables. The increase of the average of B-2 over A-2 is 22.6 per-cent and B-3 over A-3 is 54.7 per-cent. From these values it is seen that it is advantageous to cure the specimens in air after the steam treatment, but it is doubtful if the increase in strength would be as marked after 28-days as it was up to that time.

Only a few of the specimens failed suddenly, showing that the use of the damp consistency did not give a very dense product. Vertical cracks appeared first near the middle of the walls and then the specimens failed by diagonal shear. Examination of the concrete showed it to be rather crumbly and it did not offer much resistance to disintegration when rubbed between the hands. The results show conclusively that there is a marked increase in the compressive strength due to steam-curing for the periods covered in these tests.

Experiments 3 and 4.

Owing to the fact that the steam was shut off when the test pieces were partly cured it was necessary to throw out Experiment 3 and make a new series of test pieces which have been designated as Experiment 3 (repeated). However,the specimens of Experiment 3 were tested and the results recorded.

Because of the fact that the steam-curing chamber would accommodate only six specimens when set on slate pallets and because the 48 and 72-hour duration of steam-curing was found from the previous experiments to give the best results, it was decided to omit the 24-hour series of steam-curing in this experiment.

The test pieces made from concrete of wet consistency were molded as explained above, but were allowed to set in air only two hours. They were then moved on the pallets to the steam-curing chamber, except those which were to be cured in the

EXPERIMENT 3.

TO DETERMINE THE RELATIVE COMPRESSIVE STRENGTH OF STEAM-HARDENED, STEAM-CURED, AND AIR-CURED CONCRETE BUILDING TILE.

One part portland cement to four parts sand. Wet consistency 13.5 per-cent water. Tested when 7 days old.

Initial set in air 2 hours.
Average temperature of air-curing chamber 70 F.
Initial set in steam 12 hours.
Average temperature of steam during initial set 110 F.
Average temperature of steam-curing chamber 212 F.
Area of cross section 36 square inches.
Volume of specimen 216 cubic inches.

Spec. No.	Cured in Steam, hours.	Cured in Air, days.	Weight per cu. ft. when tested, pounds.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq. in.	Gain of steam-cured over air-cured specimens, per-cent.	Remarks.
C-1	48	5	138	30,700	800		Crushed at end.
C-1'	48	5	136	27,000	750		Crushed suddenly.
C-1"	48	5	138	25,000	010		Sheared at end.
Av.	48	5	138	25,900	720	9.4	
C-2	72	4	141	37,900	1,050		Crushed at middle.
C-2'	72	4	140	24,400	678		Crushed at end.
C-2"	72	4	137	26,200	730		Crushed at side, end.
Av.	72	4	139	26,166	819	24.4	
C-3	--	7	140	19,000	527		Crushed on top of spec.
C-3'	--	7	137	19,900	552		Sheared at end.
C-3"	--	7	137	32,200	895		Sheered at end sudden.
Av.	--	7	137	24,033	658	00.0	

EXPERIMENT 3.(REPEATED)

TO DETERMINE THE RELATIVE COMPRESSIVE STRENGTH OF STEAM-HARDENED, STEAM-CURED, AND AIR-CURED CONCRETE TILE.

One part portland cement to four parts sand. Wet consistency 13.5per-cent water. Tested when 7 days old.

Initial set in air 2 hours.
Average temperature of air-curing chamber 76 F.
Initial set in steam 12 hours.
Average temperature of steam during initial set 140 F.
Average temperature of steam-curing chamber 210 F.
Area of cross section 36 square inches.
Volume of specimen 216 cubic inches.

Spec. No.	Cured in Steam, hours.	Cured in Air days.	Weight per cu. ft. when tested, pounds.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq. in.	Gain of steam-cured over air-cured specimens. per-cent.	Remarks.
C'-1	48	5	138	38,600	1,070		Cracked at side.
C'-1'*	48	5	140	32,300	897		Crushed on bottom.
C'-1"	48	5	141	39,000	1,080		Sheared at side,end.
Av.	48	5	139	36,633	1,075	7.3	
C'-2	72	4	141	43,200	1,200		Sheared at side,end.
C'-2'	72	4	141	41,000	1,135		Sheared at end.
C'-2"	72	4	140	42,500	1,180		Crushed sudderly.
Av.	72	4	141	42,233	1,172	16.80	
C'-3	--	7	138	35,000	975		Sheared all sides.
C'-3'	--	7	137	34,300	955		Sheared side and end.
C'-3"	--	7	138	39,000	1,080		Crushed at end.
Av.	--	7	138	36,100	1,003	00.0	

* Crack in the specimen at the corner before placing in the machine.

EXPERIMENT 4.

TO DETERMINE THE RELATIVE COMPRESSIVE STRENGTH OF STEAM-HARDENED, STEAM-CURED, AND AIR-CURED CONCRETE BUILDING TILE.

One part portland cement to four parts sand. Wet consistency 13.5per-cent water. Tested when 28 days old.

Initial set in air 2 hours.
Average temperature of air-curing chamber 76 F.
Initial set in steam 12 hours.
Average temperature of steam during initial set 107 F.
Average temperature of steam-curing chamber 212 F.
Area of cross section 36 square inches.
Volume of specimen 216 cubic inches.
Specimens were sprinkled for 7 days after removal from steam-curing chamber.

Spec. No.	Cured in Steam, hours.	Weight per cu. ft. when tested, pounds.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq.in.	Gain of steam-cured over air-cured specimens, per-cent.	Remarks.
D-1	48	144	69,600	1,935		Failed suddenly.
D-1'	48	142	67,000	1,860		Ditto.
D-1"	48	143	61,000	1,695		Ditto.
Av.	48	143	65,866	1,830	19.4	
D-2	72	144	61,000	1,695		Sheared at end, side.
D-2'	72	147	67,500	1,875		Sheared end, side.
D-2"	72	143	73,000	2,030		Crushed at end.
Av.	72	145	67,166	1,867	21.8	
D-3	--	144	53,000	1,475		Sheared at side.
D-3'	--	142	56,800	1,580		Crushed slowly.
D-3"	--	142	55,500	1,540		Crushed slowly.
Av.	--	143	55,100	1,532	00.0	

open air. Only a small amount of steam was admitted for twelve hours, until the test pieces had set, and then they were subjected to steam at atmospheric pressure. A higher temperature would have been used were it not for the fact that a previous trial proved disastrous, as all the test pieces melted because of the saturated steam.

An examination of the Experiments 3(repeated) and 4 shows that there is an increase in the ultimate strength due to steam-curing. The maximum average gain of the steam-cured test pieces over the air-cured in Experiment 3 (repeated) is 16.8 per-cent, tested at age of 7-days and 21.8 per-cent for 28-day tests in Experiment 4. The increase in strength of the 28-day specimens over the 7-day ones for similar treatment in steam is 70 per-cent for the 48-hour steam-curing and 59.4 per-cent for the 72-hour steam-curing. The test pieces 28-days old cured in air only were 30.6 per-cent stronger than the 7-day old steam-cured test pieces cured for 72-hours in steam.

The increase in strength of the 72-hour over the 48-hour steaming is clearly seen, but the increase is not as marked as between the 24 and 48-hour steaming in Experiments 1 and 2. The ultimate strength is higher for the wet consistency of mortar and the average increase for the steam-cured specimens over those in Experiments 1 and 2 under the same treatment is 27.5 per-cent for the 7-day specimens and 31.2 per-cent for the 28-day specimens.

An examination of the wet consistency test pieces after testing showed a denser concrete which was less subject to

disintegration than the other consistencies. Failure took place suddenly in most cases and was characterized by shear rather than by any crushing in the concrete. A comparison of the above results indicates that for building tile made by the dry process in the manner herin described, the best consistency of mortar to use is 13.5 per-cent water, cured in steam for at least 72 hours.

Experiments 5 and 6.

Since the results of Experiments 3 and 4 showed clearly that the 72-hour duration of steam-curing was the most effective, this length of curing was used in these tests. F-1, E-1 were set in steam and cured in steam; series F-2, E-2 were set in steam and cured in air, while series F-3 and E-3 were set in air and cured in air.

The same molds were used in this experiment as were used before, except that metal cores replaced the wooden ones. The molds were filled by pouring and then moved to the steam-curing chamber and given a quick initial set in steam. The jacket and cores were then removed, the entire operation requiring an average of three minutes. When all had been hardened they were removed to the steam-curing chamber and subjected to steam at atmospheric pressure for 72 hours.

On removing the forms the concrete had set sufficiently so that the test pieces would stand and permit handling, but it was noticed that the top was spongy and full of small holes.

The specimens tested at 7 days were sprinkled daily for two days before testing, while the 28-day specimens were

EXPERIMENT 5.

TO DETERMINE THE RELATIVE COMPRESSIVE STRENGTH OF STEAM-HARDENED, STEAM-CURED, AND AIR-CURED CONCRETE BUILDING TILE.

One part portland cement to four parts sand. Sloppy consistency 16.5 per-cent water. Tested when 28 days old.

Time for hardening in steam 3 minutes.
Average temperature of steam during hardening process 212. F.
Average temperature of steam-curing chamber 212 F.
Average temperature of air-curing chamber 76 F.
Area of cross section 36 square inches.
Volume of specimen 216 cubic inches.
Specimens were sprinkled for 7 days after removal from the steam-curing chamber.

Spec. No.	Cured in Steam, hours.	Weight per cu. ft. when tested, pounds.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq. in.	Gain of steam-cured over air-cured specimens, per-cent.	Remarks.
E-1*	72	145	19,500	542		Crushed on top.
E-1'	72	143	18,000	500		Ditto.
E-1"	72	145	17,500	485		Ditto.
Av.	72	144	18,333	509	-52.4	
E-2	--	146	21,000	584		Crushed at side.
E-2'	--	146	29,300	815		Crushed on top.
E-2"**	--	146	30,000	834		Ditto.
Av.	--	146	26,766	744	-41.8	
E-3	--	145	52,000	1,445		Sheared at side and end.
E-3'	--	143	40,000	1,110		Sheared at end only.
Av.	--	144	46,000	1,277	00.0	

* Crack in specimen before testing.
** Uneven bearing in machine.

EXPERIMENT C.

TO DETERMINE THE RELATIVE COMPRESSIVE STRENGTH OF STEAM-HARDENED, STEAM-CURED, AND AIR-CURED CONCRETE BUILDING TILE.

One part portland cement to four parts sand. Sloppy consistency 18.5per-cent water. Tested when 7 days old.

Time for hardening in steam 3 minutes.
Average temperature of steam during hardening process 212 F.
Average temperature of steam-curing chamber 212 F.
Average temperature of air-curing chamber 76 F.
Area of cross section 36 square inches.
Volume of specimen 216 cubic inches.

Spec. No.	Cured in Steam, hours.	Weight per cu. ft. when tested, pounds.	Load at Ultimate, pounds.	Ultimate strength, pounds per sq.in.	Gain of steam-cured over air-cured specimens, per-cent.	Remarks.
F-1*	72	145	15,670	435		Crushed at top.
F-1'	72	144	22,750	630		Ditto
F-1"	72	145	16,380	455		Sheared at end.
Av.	72	145	18,267	507	-36.00	
F-2	--	145	15,000	417		Crushed on top.
F-2'	--	145	23,920	673		Ditto.
F-2"	--	143	18,000	500		Ditto.
Av.	--	144	18,973	530	-29.60	
F-3	--	144	30,630	850		Sheared at end.
F-3'	--	145	26,700	742		Crushed on top.
Av.	--	145	28,665	796	00.0	

* Crack in specimen before testing.

sprinkled for seven days. Owing to the rough top on the test pieces great care was required in bedding them before testing.

The ultimate strength in these tests does not compare favorably with those above, notwithstanding the fact that these were made from a poured mixture. There is a decrease rather than an increase in the compressive strength of the steam-cured over the air-cured test pieces. Series F-1 and E-1 which were hardened in steam have a lower compressive strength than F-2 and E-2, which were hardened in steam but cured in air. This seems to indicate that steam-curing does not increase the ultimate strength after the hardening process. A comparison of the series F-1 and E-1 shows that there is little increase in strength of the 28-day over the 7-day specimens. In series E-3 tested at 28 days there is an increase in strength of 60 per-cent over series F-3 tested at 7 days. Since the increase is not very noticeable in the specimens hardened in steam and cured in steam, seems to show that the setting or hardening of the cement had been impaired by the quick initial set.

Failure was in general by crushing at the top of the specimen and was due no doubt to the spongy condition of the top, which was caused by the emission of steam during hardening. Only a slight difference could be noticed between the appearance of the steam-hardened and the air-hardened test pieces, except that the former were somewhat lighter in color. The concrete except on the top surface was very dense and was not easily crumbled. The air-cured specimens in every case tested higher than the steam-cured ones, proving that such a treatment of

steam-hardening is of doubtful value.

Experiment 7.(Porosity Tests).

It was the object of these tests to determine whether steam-curing caused any change in the make-up of the structure, so as to render it more waterproof.

Referring to the tables, the specimens in Experiment 7 were those tested in the foregoing experiments on compressive strength. The porosity tests were made before the specimens were prepared for the compression tests. The test pieces were placed in water for twenty minutes and removed to a drip rack for five minutes before weighing. Before bedding in plaster the specimens were again weighed. The porosity was based on the gross volume of the dry specimen. An examination of the table shows that the most porous test pieces are those made from the mortar of damp consistency, which had received the initial set in air and which had been cured in air. The test pieces of series A-2 , A-3 , and B-2 , B-3 , which had been cured in steam 48 and 72 hours respectively absorbed less water than those cured in steam 24 hours or those cured in air only. The air-cured test pieces 7-days old were only 1.6 per-cent more porous than those 28-days old. Series B-3 proved to be the least porous of any.

The test pieces made from the mortar of wet consistency ranged from 7.3 per-cent in series D-2 to 16.1 per-cent in C and as in series A and B the air-cured specimens were the most porous. The amount of water absorbed in specimens of series D was much

less than that absorbed in either series C or C'. Series C' and C have similar average porosity values, there being only a slight difference between the results from the steam-cured and the air-cured test pieces. The lower values in series D may be accounted for by the fact that the specimens may have been tamped harder than those of either series C or C'. The results of the ultimate compressive strength in Experiment 4 are high, which seems to show that it was dense concrete.

The test pieces made from the mortar of Sloppy consistency were the least porous of any. Since no tamping was required in the molding of test pieces in Experiments E and C, the results may be expected to be more consistent than those which might be obtained from the hand tamped test pieces. The air-cured specimens 7-days old were the most porous, with 4.72 per-cent absorption, while the 28-day air-cured specimens gave 3.6 per-cent. In the above series the porosity varied with the duration of steam-curing, but in series E-1 this is not the case since the steam-cured specimens exceeded the air-cured ones by 2.2% per-cent. However the steam-cured test pieces in F-1 were less porous than any of the air-cured specimens in the same series.

In Experiments 3-4 those specimens which were cured in steam were more difficult to remove from the pallets than those cured in air, which seemed to indicate that some change had taken place in the structure of the concrete. This fact together with the results of the compressive tests of these specimens show that steam-curing does, in a measure, cause a change to take place in the structure of the concrete after it

has been placed in the mold, thus rendering it in a small degree more impervious to water.

In an attempt to determine the amount of absorption, it is difficult to get values that agree exactly, owing to the fact that each specimen may be tamped differently, with a result that one test piece becomes more dense than another. In making comparisons of the above experiment it is well to bear in mind the conditions under which the several test pieces were made.

EXPERIMENT 7.

POROSITY OF STEAM-CURED AND AIR-CURED CONCRETE BUILDING TILE.

One part portland cement to four parts sand.

Spec. No.	Initial set.	Cured in,	Consistency of mixture.	Weight dry, pounds.	Weight wet, pounds.	Water absorbed, pounds.	Absorption by volume, per-cent.
A-1	Air	Steam	Damp	17.0	18.6	1.6	
A-1'	"	"	"	16.8	18.5	1.7	
Av.	"	"	"			1.65	21.0
A-2	"	"	"	17.1	18.4	1.3	
A-2'	"	"	"	16.9	18.5	1.6	
A-2"	"	"	"	17.0	18.6	1.6	
Av.	"	"	"			1.5	19.2
A-3	"	"	"	16.9	18.6	1.7	
A-3'	"	"	"	17.1	18.5	1.4	
A-3"	"	"	"	17.1	18.6	1.5	
Av.	"	"	"			1.54	19.7
A-4	"	Air.	"	16.8	18.5	1.7	
A-4'	"	"	"	16.7	18.5	1.8	
Av.	"	"	"			1.75	22.4
B-1	"	Steam	"	17.0	18.3	1.3	
B-1'	"	"	"	17.0	18.2	1.2	
B-1"	"	"	"	17.0	18.2	1.2	
Av.	"	"	"			1.23	15.75
B-2	"	"	"	17.1	18.1	1.0	
B-2'	"	"	"	17.1	18.2	1.1	
B-2"	"	"	"	17.1	18.3	1.2	
Av.	"	"	"			1.1	14.1
B-3	"	"	"	17.3	18.2	.9	
B-3'	"	"	"	17.3	18.2	.9	
B-3"	"	"	"	17.4	18.2	.8	
Av.	"	"	"			.87	11.1
B-4	"	Air	"	17.0	18.5	1.5	
B-4'	"	"	"	16.8	18.5	1.7	
B-4"	"	"	"	16.8	18.5	1.7	
Av.	"	"	"			1.68	20.8
C-1	Steam	Steam	Wet	17.3	18.6	1.3	
C-1'	"	"	"	17.3	18.6	1.3	
C-1"	"	"	"	17.3	18.5	1.2	
Av.	"	"	"			1.26	16.1
C-2	"	"	"	17.6	18.9	1.3	
C-2'	"	"	"	17.5	18.7	1.2	
C-2"	"	"	"	17.1	18.4	1.3	
Av.	"	"	"			1.26	16.1
C-3	Air	Air	"	17.5	18.7	1.2	
C-3'	"	"	"	17.1	18.4	1.3	
C-3"	"	"	"	17.1	18.4	1.3	
Av.	"	"	"			1.26	16.1

EXPERIMENT 7. (continued).

Spec. No.	Initial set.	Cured in,	Consistency of mixture.	Weight dry, pounds.	Weight wet, pounds.	Water absorbed, pounds.	Absorption by volume per-cent.
C'-1	Steam	Steam	Wet	17.3	18.6	1.3	
C'-1'	"	"	"	17.5	18.7	1.2	
C'-1"	"	"	"	17.65	18.8	1.13	
Av.	"	"	"			1.21	15.5
C'-2	"	"	"	17.65	18.8	1.15	
C'-2'	"	"	"	17.65	18.8	1.15	
C'-2"	"	"	"	17.5	18.65	1.15	
Av.	"	"	"			1.15	14.7
C'-3	Air	Air	"	17.3	18.6	1.3	
C'-3'	"	"	"	17.3	18.4	1.1	
C'-3"	"	"	"	17.3	18.6	1.3	
Av.	"	"	"			1.23	15.75
D-1	Steam	Steam	"	18.0	18.6	.6	
D-1'	"	"	"	17.8	18.6	.8	
D-1"	"	"	"	17.9	18.6	.7	
Av.	"	"	"			.7	8.95
D-2	"	"	"	18.0	18.5	.5	
D-2'	"	"	"	18.4	18.9	.5	
D-2"	"	"	"	17.9	18.6	.7	
Av.	"	"	"			.57	7.3
D-3	Air	Air	"	18.0	18.6	.6	
D-3'	"	"	"	17.75	18.6	.85	
D-3"	"	"	"	17.75	18.6	.85	
Av.	"	"	"			.77	9.85
E-1	Steam	Steam	Sloppy	18.15	18.4	.25	
E-1'	"	"	"	17.9	18.4	.50	
E-1"	"	"	"	18.15	18.4	.25	
Av.	"	"	"			.33	4.2
E-2	"	Air	"	18.25	18.5	.25	
E-2'	"	"	"	18.25	18.4	.15	
E-2"	"	"	"	18.25	18.3	.05	
Av.	"	"	"			.15	1.92
E-3	Air	"	"	18.15	18.4	.25	
E-3'	"	"	"	17.9	18.4	.50	
Av.	"	"	"			.37	4.72
F-1	Steam	Steam	"	18.15	18.4	.25	
F-1'	"	"	"	18.0	18.3	.30	
F-1"	"	"	"	18.15	18.4	.25	
Av.	"	"	"			.27	3.45
F-2	"	Air	"	18.15	18.4	.25	
F-2'	"	"	"	18.15	18.4	.25	
F-2"	"	"	"	17.9	18.4	.50	
Av.	"	"	"			.33	4.2
F-3	Air	"	"	18.0	18.3	.30	
F-3'	"	"	"	18.15	18.3	.15	
Av.	"	"	"			.23	3.63

Summary of Tests.

Although there are many combinations of proportions of sand and cement, and temperatures of steam which might have been used in carrying out a series of tests of this kind, it is believed that the above proportions, and temperatures employed are those which would be used by the average manufacturer in production of building tile, and that the results are a fair average of what could be expected in practice.

The results from the seven foregoing experiments can be summarized in the following conclusion:

1- Steam-curing increases the compressive strength of concrete and renders it as strong after 48-hours in steam and 5-days in air, as it ordinarily is when cured in the open air for 28-days.

2- The compressive strength increases with the length of curing up to 72-hours, when under steam at atmospheric pressure.

3- For steam-curing the Wet consistency is preferable to the Damp consistency or the Sloppy consistency.

4- Giving concrete a partial initial set in steam does not decrease its compressive strength.

5- Steam-hardening (giving a quick initial set) decreases the strength of the concrete.

6- Steam-curing causes the concrete to be more waterproof.

7- Steam-curing produces a concrete of more uniform appearance and lighter in color than that made from the same materials and cured in the open air.

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